EVOLUTION OF LYMAN BREAK GALAXIES FROM Z=5 TO 3

Ikuru Iwata
Okayama Astrophysical Observatory, National Astronomical Observatory of Japan

Kouji Ohta, Masataka Ando, Gaku Kiuchi
Department of Astronomy, Faculty of Science, Kyoto University, Japan

Naoyuki Tamura
Department of Physics, University of Durham, UK

Masayuki Akiyama and Kentaro Aoki
Subaru Telescope, National Astronomical Observatory of Japan

Abstract. We report the updated UV luminosity function (LF) of Lyman break galaxies at $z \sim 5$. Combining with lower redshift data, we found that the evolution of UV LF is differential depending on the UV luminosity. With results from clustering analysis, optical spectroscopy and SED fitting, it is suggested that this differential evolution might be understood as a consequence of biased galaxy evolution.

1 Introduction

In the last ten years many deep surveys using *HST* and ground-based facilities have been carried out, and we have gradually enlarged our knowledge on the nature of galaxies in the early universe. The Lyman break technique, which was first developed by C. Steidel and his co-workers, is one of the simplest and most successful methods to extract galaxies at target redshift ranges from deep survey images. Past studies have successfully constructed a large samples of Lyman break galaxies (LBGs) mainly at $z \lesssim 3$, and follow-up studies have gradually revealed their properties (e.g., Steidel et al. 2003; Sawicki and Yee 1998; Papovich et al. 2001; Shapley et al. 2003; Adelberger et al. 2005).

A unique combination of the large mirror, wide-field camera and excellent image quality of Subaru telescope enabled us to proceed toward higher redshift, approaching to the epoch of galaxy formation. In 2001 our team pointed the telescope to the HDF-N/GOODS-N area and made multi-band optical imaging aiming at the survey of LBGs at $z \sim 5$. We have successfully detected more than 300 LBG candidates with $I_c \leq 26.0$ [1] as the world's first large sample of LBGs at $z \sim 5$ (Iwata et al. 2003). Follow-up spectroscopy using FOCAS revealed that relatively bright 7 objects ($I_c \leq 25.0$) are indeed at $z \sim 5$ (Ando et al. 2004). Other teams using Subaru have also made systematic census of LBGs at $z \sim$4–6 (e.g., Ouchi et al. 2004; Shimasaku et al. 2005). Although the surveyed area is quite narrow, the Hubble Ultra Deep Field project put constraints on the number density of LBGs at $z \gtrsim 6$ (e.g., Bouwens et al. 2004, 2005; Bunker et al. 2004).

In this contribution, we would like to report the updated UV luminosity function for LBGs at $z \sim 5$, as well as some results from follow-up observations, clustering analysis and SED fitting using public released data from GOODS (Giavalisco et al. 2004). A discussion on the evolution of LBGs is also presented.

2 Sample

Optical imaging data from which we have selected sample of LBGs at $z \sim 5$ were taken with Subaru / Suprime-Cam (Miyazaki et al. 2002), which has a $34' \times 27'$ field of view. There are two target fields, namely the Hubble Deep Field - North (HDF-N) and J0053+1234 (Cohen et al. 1996). The HDF-N data were taken in 2001 by us and the UH group (Capak et al. 2004; taken from archive system SMOKA). J0053+1234 data have been taken from 2002–2004 by us. The limiting magnitudes of images ($1.2''\phi$ aperture, 5σ) for the HDF-N and J0053+1234 were 28.2(V), 26.9(I_c), 26.6 (z') and 27.8(V), 26.4(I_c), 26.2(z'), respectively.

The color selection criteria for LBGs at $z \sim 5$ we have adopted were same as those described in Iwata et al. (2003); $V - I_c \geq 1.55$ and $V - I_c \geq 7(I_c - z') + 0.15$. The number of LBG candidates are 617 ($z' < 26.5$) for HDF-N and 246 ($z' < 25.5$) for J0053.

[1] All magnitudes are in AB

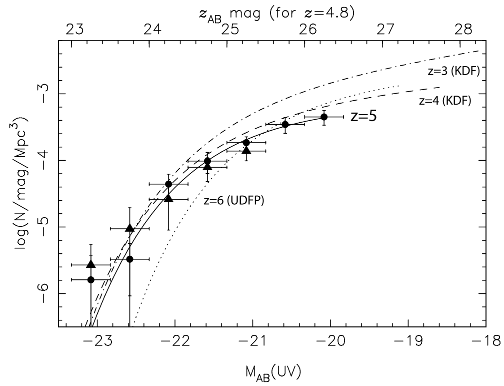

Figure 1: UV luminosity function (LF) of LBG samples from $z \sim 6$ to $z \sim 3$. UV LFs for $z \sim 5$ are for HDF-N(circles) and J0053+1234(triangles). Schechter function fits for other redshifts are from $z \sim 6$: Bouwens et al. (2004), $z \sim 3$ and 4: Sawicki and Thompson (2005).

3 UV Luminosity Function and Optical Spectroscopy

In figure 1 we show the UV luminosity function for our $z \sim 5$ LBG samples, as well as those from Keck Deep Fields (Sawicki and Thompson 2005) for $z \sim 3$–4 and UDF-Parallel (Bouwens et al. 2004) for $z \sim 6$. From redshift 5 to 3, the number density of UV luminous objects does not show significant change. However, the number density of faint $L < L^*$ galaxies is increasing by a factor of ≈5, although our $z \sim 5$ sample is more than 1 mag shallower than those for lower redshifts. This indicates that the number density evolution is differential depending on the UV luminosity (see also a contribution by M. Sawicki in this volume).

On the other hand, UV LF for LBGs at $z \sim 6$ might show significant drop in the bright part (e.g., Bouwens et al. 2004; Bunker et al. 2004). If it is the case, drastic evolution may have occurred from $z \sim 6$ to 5. Note that $z \sim 6$ is considered to be an epoch of the end of the cosmic reionization (Fan et al. 2001; Cen 2003).

We have made optical spectroscopy for limited number of sample LBGs with Subaru/FOCAS (Kashikawa et al. 2002). So far nine luminous ($L > L^*$) LBGs have been identified as objects at $z \sim 5$ (Ando et al. 2004; Ando et al. in prep.). There is significant absence of strong Lyα emission for luminous LBGs at $z \sim 5$, which is not apparent for $z \sim 3$ LBGs (e.g, Shapley et al. 2003). In the spectra of those LBGs, we also see strong interstellar low-ionization metal lines such as SiII, SiIV and CII. These features might be attributed to (1) relatively dusty and metal-rich environment of luminous LBGs, or (2) massive neutral gas reservoirs around the star-forming galaxies. More detailed descriptions of spectroscopic results are presented in a separate contribution by M. Ando.

4 Clustering and Stellar Populations

We derived the two-point correlation function for our $z \sim 5$ LBGs. Clustering signals were detected (figure 2, left), and there seems to be a trend that UV luminous objects showed stronger clustering than fainter ones, as it has been reported for $z \lesssim 3$ LBGs (e.g., Giavalisco and Dickinson 2001; Adelberger et al. 2005). Correlation lengths of $z \sim 5$ LBGs (figure 2, right) are slightly larger than LBGs at lower redshifts and are comparable to Distant Red Galaxies and Sub-mm galaxies, many of both populations are considered to be active star forming galaxies (Iwata et al. 2005; Blain et al. 2004). It is suggested that UV luminous LBGs at $z \sim 5$ are hosted by massive dark matter halos, which could grow into host halos of giant galaxies in the present universe.

The cross-identification of our sample LBGs with the Spitzer/IRAC images in the public data release (DR1) from the GOODS have been made. Although the survey depths and coverage are still limited, about 100 objects were detected in IRAC channel 1 and/or 2. In figure 3 (left) we show a correlation between IRAC flux and rest-frame UV-to-optical colors. The absence of luminous LBGs with blue colors is clearly seen. This trend might be partly due to the dusty environment in luminous LBGs. However, it might be a natural consequence of the existence of evolved stellar populations, since IRAC channel 1 and 2 trace rest-frame ≈6,000–8,000Å.

We have also tried to obtain K'-band images for limited number of sample galaxies with Subaru/CISCO. With these near- and mid-IR data we have carried out SED fitting. For calculating flux densities of sample galaxies in IRAC we tested both $1.''6$ aperture (same as used in optical data) photometry with corrections for larger PSFs of IRAC data and `mag_auto` in SExtractor (Bertin and Arnouts 1996), and found that the

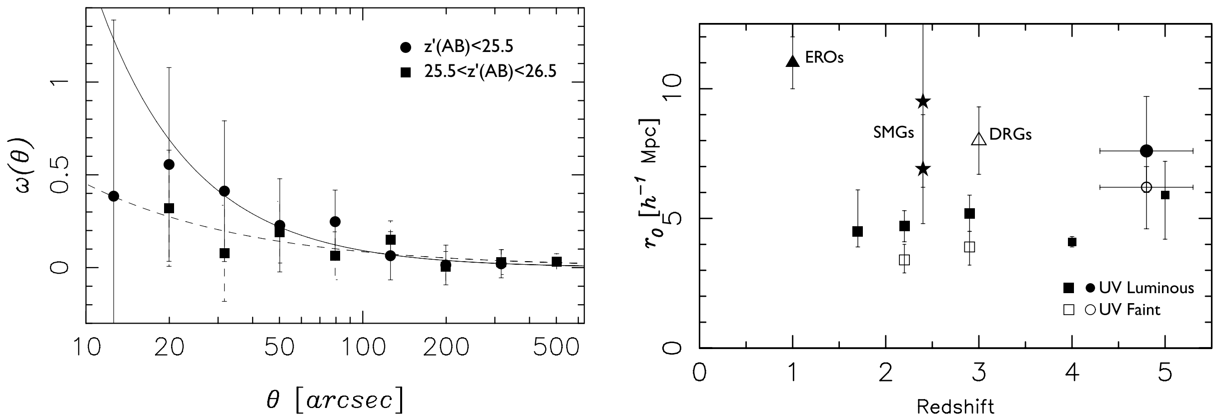

Figure 2: (Left)Correlation functions of luminous (circle) and faint (square) LBGs at $z \sim 5$. (Right): Comparison of correlation lengths for various populations at different $1 \lesssim z \lesssim 5$. Data points other than ours at $z = 4.8$ are from Adelberger et al. (2005; LBGs at $z \sim$ 2–3), Ouchi et al. (2004; LBGs at $z \sim$4–5), Miyazaki et al. (2004; EROs), Blain et al. (2004; SMGs) and Daddi et al. (2003; DRGs).

differences in estimates are well within 68% confidence intervals. Model spectra were generated by version 2 of PEGASE (Fioc & Rocca-Volmerange 1997). Two simplified star formation histories were calculated, namely, constant star formation rate (SFR) and exponentially-decaying star formation (τ =10–1,000 Myr). One of the results from this preliminary analyses with constant SFR models is shown in figure 3 (left). Fairly tight correlation between the IRAC (rest-frame optical) flux densities and stellar mass estimates is found, and there are some optically luminous galaxies which have already accumulated $\gtrsim 10^{10} M_\odot$ stellar mass at $z \sim 5$. We also found that there seems to be a tendency that luminous LBGs are subject to slightly larger dust attenuation, which might be qualitatively consistent with results from spectroscopy, but the degeneracy of dust attenuation and stellar ages in the current data set prevents us to reach the definitive conclusion at the moment.

5 A Possible Scenario: Biased Galaxy Evolution

These observational results coming from deep imaging and spectroscopy as well as multi-wavelength data might open out a new perspective of the galaxy evolution at the universe age less than 2 Gyr. If we assume that actively star-forming galaxies (=UV luminous galaxies) have larger amount of gas (suggested from optical spectroscopy) and are hosted by more massive DM halos (suggested from the difference in clustering amplitude), the differential evolution of UV LF can be closely connected to the biased galaxy evolution scenario: Star formation started selectively in rare peaks of mass density at $z > 5$. Such most massive DM halos host large amount of baryons as well, and the active star formation would be ignited (resulting fairly large amount of dust and metals). As time passes the clustering of DM halo grows and star formations gradually take place within less massive DM halos, which are more common in the universe. This would result in the increase of fainter objects by $z \sim 3$.

Moreover, this scenario could be put into a larger view of the galaxy evolution throughout the cosmic time. From recent studies it seems that the star formation density in the universe gradually increase from $z \sim 6$, reached to the highest level around z = 3–2 then slowly declines until the current epoch(e.g., Bunker et al. 2004). The increase at higher redshift should be caused by the differential UV LF evolution, and the decline at low-z would be tightly connected to the "down-sizing" effect (Cowie et al. 1996; Kodama et al. 2004); i.e., the massive galaxies stops star formation in earlier epochs and less massive ones continue to form stars. With more thorough investigation for high-z biased galaxy evolution (as we describe below), we would be able to unify it with the "down-sizing" effect and depict an overall evolution viewgraph of galaxies from the cosmic age of 1 Gyr to 13 Gyr, as schematically illustrated in figure 4.

Although this scenario qualitatively explains all of our findings consistently, that does not mean it is the unique solution. There are some alternative possibilities: there might be a change in the properties of starburst (frequency, intensity, or duty cycle of burst-quiescent loops) from $z \sim 5$ to $z \sim 3$, or differential dust properties might be also able to reproduce some of observed trends (Sawicki and Thompson 2005). We should also consider that LBGs are by definition UV luminous star-forming galaxies with relatively small amount of dust attenuation, and some part of LBGs at higher redshift would be missed when they are observed at lower redshift, due to passive evolution or larger amount of dust (like sub-mm galaxies). Although we think that a new perspective

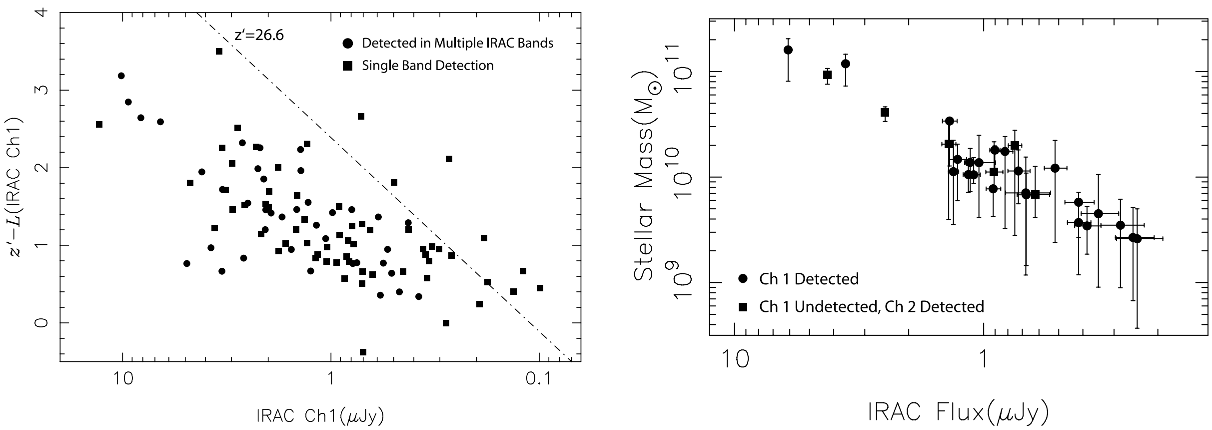

Figure 3: (Left): IRAC flux densities (in channel 1 or 2) and $z' - L$ colors, which corresponds to the rest-frame UV-to-optical colors. (Right): one example of results of SED fitting for IRAC-detected LBGs at $z \sim 5$. stellar mass estimates are plotted along with IRAC flux densities.

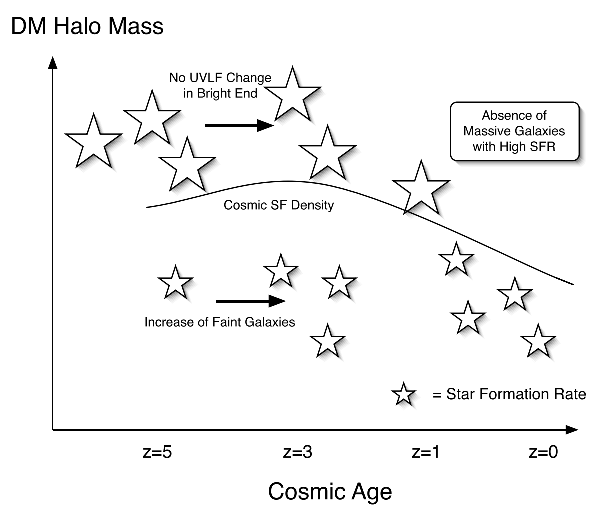

Figure 4: A schematic illustration of the unified view of the "biased galaxy evolution" at $z \gtrsim 3$ and "down-sizing" of $z \lesssim 2$.

for a comprehensive understanding of galaxy evolution throughout the cosmic time began to open out for us, various kinds of improved data would be required to go further. Deeper images in optical, infrared and sub-mm wavelengths for the construction of the complete samples and more reliable stellar population / dust amount estimations through SED fitting, and much more spectroscopic identifications to obtain insights on matallicities and gas kinematics within galaxies. We expect that such data would be helpful for the improvement of ingredients of cosmological numerical simulations, to consistently predict properties of star-forming galaxies at wide range of redshifts.

Acknowledgements. We thank M. Sawicki for providing their results for UV LF at z ∼2–4 and valuable discussions. A part of this study is based on data collected at Subaru Telescope and obtained from the SMOKA science archive at Astronomical Data Analysis Center, which are operated by the National Astronomical Observatory of Japan.

References

[1] Adelberger K., et al. 2005, ApJ 619, 697

[2] Ando et al. 2004, ApJ 610, 635

[3] Berstein and Arnouts 1996, A&AS 117, 393

[4] Blain et al. 2004, ApJ 611, 725

[5] Bouwens et al. 2004, ApJ 606, L25

[6] Bouwens et al. 2005, ApJ 624, L5

[7] Bunker et al. 2004, MNRAS 355, 374

[8] Capak et al. 2004, AJ 127, 180

[9] Cen 2003, ApJ 591, 12

[10] Cohen et al. 1996, ApJ 462, L9

[11] Cowie et al. 1996, AJ 112, 839

[12] Daddi et al. 2003, ApJ 588, 50

[13] Fan et al. 2001, 122, 2833

[14] Fioc and Rocca-Volmerange 1997, A&A 326, 950

[15] Giavalisco and Dickinson 2001, ApJ 550, 177

[16] Giavalisco et al. 2004, ApJ 600, L93

[17] Iwata et al. 2003, PASJ 55, 415

[18] Iwata et al. 2005, A&A 440, 881

[19] Kashikawa et al. 2002, PASJ 54, 819

[20] Kodama et al. 2004, MNRAS 350, 1005

[21] Miyazaki, S., et al. 2002, PASJ, 54, 833

[22] Miyazaki et al. 2004, PASJ 55, 1079

[23] Ouchi et al. 2004, ApJ 611, 685

[24] Papovich et al. 2001, ApJ 559, 620

[25] Sawicki and Thompson 2005, submitted to ApJ (astro-ph/0507519)

[26] Sawicki and Yee 1998, AJ 115, 1329

[27] Shapley et al. 2003, ApJ 588, 65

[28] Shimasaku et al. 2005, PASJ 57, 447

[29] Steidel et al. 2003, ApJ 592, 728